

Non-equilibrium superconductivity in a correlated electron system studied with the Keldysh+FLEX approach

Takashi Oka, Hideo Aoki

Department of Physics, the University of Tokyo, Hongo, Tokyo 113-0033, Japan

Abstract

Non-equilibrium phase transitions are studied theoretically for the two-dimensional Hubbard model subject to bias voltages from the electrodes coupled to the system. By combining the fluctuation exchange approximation with the Keldysh method for non-equilibrium, we have studied the properties of the non-equilibrium Fermi liquid phase and determined the phase diagram with transition to non-equilibrium magnetic and superconducting phases.

Key words: Nonequilibrium superconductivity, Hubbard model, 74.40.+k, 05.30.-d, 71.10.-w

1. Nonequilibrium Superconductivity and Electron Correlation

Due to the decades of research for the HTC cuprates, organic superconductors and other classes of materials, the understanding of correlated electron systems is becoming matured. One novel avenue to pursue is alternative methods for doping other than the conventional chemical doping. One way is to inject carriers from interfaces or electrodes which has been recently realized in oxides heterostructures[1]. If we consider the case where two electrodes are attached, then by adjusting the bias voltage across the electrodes, we can introduce carriers whose distribution may be different from equilibrium. The effect of such non-equilibrium carriers in correlated electron systems has been theoretically proposed recently by the present authors [2]. The main interest is whether superconductivity can occur in non-equilibrium in an open, two-dimensional correlated electron system coupled to electrodes (Fig. 1 (a)). We have adopted the Hubbard model as a standard model for correlated electron systems. The non-equilibrium situation is treated with the Keldysh formalism, while the

many-body effect with the FLEX approach[2]. We also note that non-equilibrium methods for doping cuprates have been experimentally realized in ref. [3] where photoinduced superconductivity in HTC materials was observed. Our approach is expected to shed light to these systems as well.

2. Nonequilibrium Phase Diagram and Superconducting Order

We consider a thin layer of strongly correlated material described by the two-dimensional Hubbard model which is coupled to electrodes. Here we assume that the electrodes are attached in the vertical direction (Fig. 1 (a)) and double step Fermi distribution is realized in the correlated system (Fig. 2).

In non-equilibrium systems, an important effect of the electron-electron interaction is the smearing of the electron distribution function. As can be seen in Fig. 2, the double step Fermi distribution f_{eff}^0 realized by the electrode and bias V becomes smeared into a smooth non-equilibrium distribution function f_{eff} . In this *non-equilibrium Fermi liquid* phase the bias voltage V effectively plays a similar role as the

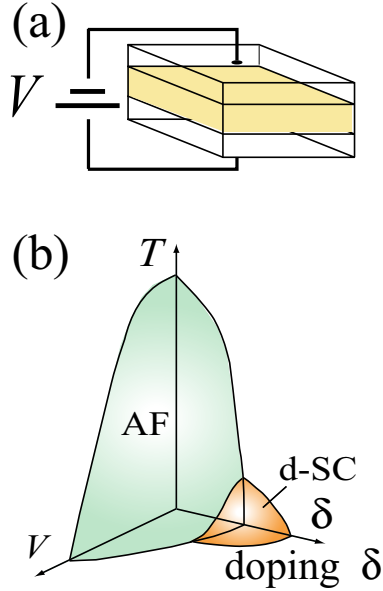


Figure 1: (a) Two dimensional correlated system (shaded) in a finite bias V . (b) Obtained non-equilibrium phase diagram against the bias (V), temperature (T), and the doping level (δ) with antiferromagnetic (AF) and d-wave superconducting (SC) phases.

temperature since the smearing of the distribution becomes stronger as one increase V .

The non-equilibrium phase diagram obtained within the Keldysh + FLEX method is schematically shown in Fig. 1 (b). Away from half-filling, for which FLEX is expected to be applicable, the superconducting gap function with d -wave symmetry dominates even in finite bias voltages. However, as one increases the bias, we can see that both the AF and SC phases become suppressed. Indeed, this can be seen in Fig. 3 (b). First at bias $V = 0.1$, which is near the non-equilibrium Fermi liquid to d-wave superconductor transition, the AF fluctuation is sharp and has multiple peak structure which reflects the incommensurate nesting. However, as one goes far away from the transition ($V = 0.2$), the peak becomes smaller and the structure vanishes.

The suppressed orderings can be understood in terms of the change in the non-equilibrium electron distribution. The AF fluctuation is induced by

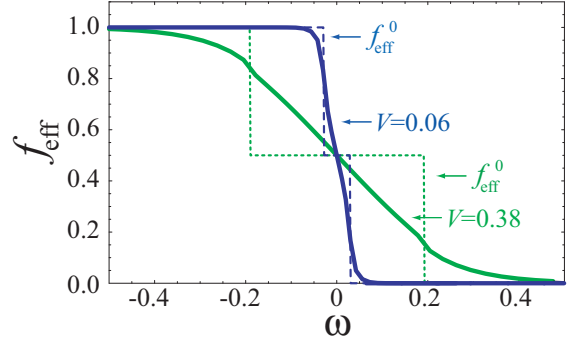


Figure 2: Nonequilibrium distribution function for two values of the bias V at half filling ($\delta = 0$). Dashed lines are the noninteracting distribution function f_{eff}^0 .

electron-electron scattering across the Fermi surface which is enhanced near half-filling due to nesting effect. However, in the presence of finite bias V , (i) the Fermi surface becomes split into two with Fermi energies $E_F \pm V/2$ where E_F is the original Fermi energy, and (ii) smearing takes place. The first effect reduces the nesting while the second weakens the scattering. The AF fluctuation is the glue for the transition from (non-equilibrium) Fermi liquid to d-wave superconductivity and the reduction of the fluctuation results in the destruction of the superconducting phase.

In conclusion, we have studied the transition between the non-equilibrium Fermi liquid, AF magnetic order and d-wave superconductor which is controllable by the applied bias. Finally we comment on the smearing effect which destroys the long range order in finite bias. In the Keldysh + FLEX method, the self-consistent treatment of the Green's function tends to overestimate the smearing effect. If the smearing is not as strong, there is a possibility that a new order appears which does not exist in equilibrium [4].

References

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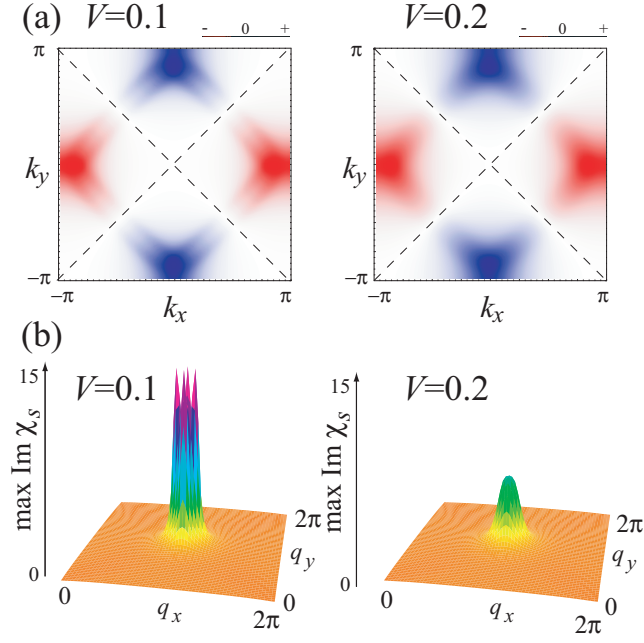


Figure 3: (a) Superconducting gap function $\text{Re } \phi(\mathbf{k}, \omega = 0)$ in non-equilibrium. The bias is $V = 0.1, 0.2$. Dashed lines represent nodes. (b) Spin susceptibility $\chi(\mathbf{q}, \omega = 0)$ for $V = 0.1, 0.2$. For $\delta = 0.14$, $U = 4.5$, and $\mu = -0.35$.

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Abstract

Key words:

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